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RESEARCH ARTICLE

Estimation of Carbon Dioxide Sequestration and Litter Production in Rehabilitated Mangrove Ecosystems

Efriyeldi[1, 2, *], Aras Mulyadi[1, 2], and Nawari[2]
[1] Department of Marine Science, Faculty of Fisheries and Marine Sciences, Universitas Riau, Pekanbaru, Indonesia.
[2] Doctoral of Environmental Science Study Program, Postgraduate, Universitas Riau, Pekanbaru, Indonesia

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Correspondent email :
efriyeldi@lecturer.unri.ac.id

Abstract. The ability of mangrove to sequestrate carbon dioxide (CO_2) is becoming part of the methods for climate change mitigation due to the ability of plants to absorb and store CO_2 from the atmosphere as biomass. Therefore, this research aimed to estimate CO_2 sequestration and litter production by *Avicennia alba* planted in mangrove rehabilitation area. The data collection method was field observation which was used to measure tree parameters and litter on the observation plot. Tree biomass was estimated using the allometric equation and converted to carbon sequestration. Moreover, a one-way Analysis of Variance (ANOVA) test was applied to assess biomass and litter production differences in the observed stations. Regression analysis was also used to diagnose the relationship between tree diameter, biomass, and carbon sequestration. The results showed that the average biomass and carbon storage at tree level were directly proportional to tree diameter and age. At the stand level, biomass and carbon sequestration in the three stations were not significantly different at the 95% confidence level. It was also observed that stem density affected mangrove biomass. The results showed that more mangrove mortality occurred with older ages at the observed stations and this lowered the stem density and biomass. Furthermore, the relationship between diameter, biomass, and carbon sequestration was directly proportional. Litter production also increased directly with tree age and diameter but the trend was insignificant. The leaf part was found to be the most significant contributor to litter production, and the proportion increased with age and diameter. These results were essential information for future sustainable mangrove rehabilitation plans.

1. Introduction

Carbon dioxide (CO_2) and other greenhouse gases (GHG) emissions are often due to several environmentally unfriendly activities, such as forest fires and deforestation, unsustainable agriculture, and the use of fossil fuels, causing global warming or climate change (Omotoso & Omotayo, 2024; Mannan & Al-Ghamdi, 2022). Global warming has subsequently caused several adverse effects on survival, such as rising sea levels, increased intensity of extreme weather phenomena, and changes in the amount and pattern of precipitation (Bedair et al., 2023). The other consequences include the impact on agricultural products, the loss of glaciers, and the extinction of different flora and fauna (Atabey & Topcu, 2017).

An example of the efforts implemented to mitigate global warming is the increase in the vegetated land cover (Alkama et al., 2022). This is necessary to increase carbon absorption and storage in order to stabilize the concentration of CO_2 and greenhouse gases in the atmosphere (Zhang et al., 2023). The ecosystem found in coastal areas and considered important in preventing natural disasters and global warming is mangrove forest (Sunkur et al., 2023). The ability of mangrove to absorb CO_2 can reduce the potential for global warming (Sumarmi et al., 2021). This is because mangrove ecosystems absorb and turn carbon into oxygen released into the air to meet human needs during photosynthesis (Djumanto, 2020). Moreover, some absorbed carbon is stored as biomass (Banerjee et al., 2021) and the trend shows the importance of the ecosystem in climatical processes by capturing and storing carbon in large amounts more than tropical forests (Sandilyan & Kathiresan, 2012). It is also useful in reducing CO_2 levels caused by fossil fuel consumption. The ecosystem is important because approximately 15% of the total carbon accumulation in the ocean comes from forests. Another benefit is the role as a nutrient contributor to coastal waters. The importance of mangrove ecosystems has led to the effective documentation of its capacity to absorb and retain organic carbon from tree biomass and sediments (Alongi, 2014; Kusumaningtyas et al., 2019; Jennerjahn, 2020).

The current problem faced in coastal areas is the large number of mangrove ecosystems degraded through human actions, such as illegal logging and land conversion (Ferreira et al., 2022). Some were damaged by natural factors such as hurricanes, tsunamis, and storm surges in certain seasons (Bhowmik et al., 2022). Moreover, there is a reduction in the land area of the ecosystem due to over-exploitation and conversion for shrimp farming, aquaculture, and agriculture (Brander et al., 2012; Akram et al., 2023; Owuor et al., 2019). The degradation has caused a reduction in carbon stocks (Kauffman et al., 2014; Eid et al., 2019; Peneva-Reed et al., 2021), leading to the need for social action plans such as conserving the intact mangrove ecosystems and restoring the degraded land (Damastuti et al., 2022). This is also necessary because mangrove forests are the primary source of food for different marine invertebrates and detritus-eating organisms (Kamruzzaman et al., 2017; Larjavaara & Muller-Landau, 2013; Lee et al., 2014; Mchenga & Ali, 2017).

Rehabilitation is part of the methods to restore the degraded land and increase mangrove area (Arifanti et al., 2022). An example is the community-based blue carbon project which focuses on providing incentives known as payments of environmental services (PES) to mangrove ecosystems well-managed by communities in order to reduce emissions through carbon capture and storage. The program can improve the sustainability of mangrove forest management (Gevaña et al., 2018). Some of the indicators developed to measure its effectiveness in reducing CO_2 emissions include carbon stock value at the start and the end of the implementation period (Liu et al., 2024). This is necessary to identify factors capable of contributing to an increase in the productivity of mangrove ecosystems in the future (Rovai et al., 2021).

An example of mangrove rehabilitation areas in Riau Province is Kedabu Rapat Village, Meranti Islands District. The species planted in the area include *Avicennia alba* with the plantation initiated in 2017 and continued yearly in 2018 and 2019. *Avicennia alba* was planted on the mud bed formed by constructing wave breakers in the form of gabions to protect the coast from the waves of Malacca Strait (Khawarizmi et al., 2021). The plant was included due to its ability to reduce coastal erosion, contribute nutrients to the waters through litter and detritus, and reduce global warming by absorbing CO_2 from the atmosphere. The difference in the ages of *Avicennia alba* contributed to biomass, carbon storage, CO_2 sequestrations, and litter production in varying amounts, showing the need for more research on the trend. Therefore, this research aimed to estimate CO_2 sequestration and litter production of *Avicennia alba* which was planted in the mud bed formed behind the gabion stone building as a wave breaker in the rehabilitation area of Kedabu Rapat Village. The results were expected to provide essential information for future mangrove rehabilitation and conservation sustainable plans.

2. Methods

The research area was the rehabilitation mangrove area at Kedabu Rapat Village, Meranti Islands District, Riau Province, Indonesia, as presented in Figure 1. The focus was on three stations which were used to represent the planting periods, 2017, 2018, and 2019. Moreover, the research was conducted from April to October 2023 with carbon sequestrations and litter production estimated by measuring the sample plots. Previous research showed that the vegetation sample plot for carbon storage was square 10x10 m^2 (Kiruba-Sankar et al., 2018) and 1x1 m^2 for litter production (Brühl et al., 2003). This research used three transects to cover the lower (1), middle (2), and upper zones (3) which led to the usage of nine pairs of vegetation and litter plots in the exact area. The parameters of tree measured were the number and diameter at breast height (dbh) in the first week of plot establishment while the weight of litter was determined every four weeks.

Carbon stock of *Avicennia alba* was obtained through biomass measurements using non-destructive methods. This was achieved through the application of allometric equations to estimate aboveground (AGB) biomass as a function of tree dbh as follows (Komiyama et al., 2008):

$$AGB = 0.308 * DBH^{2.11} \tag{1}$$

$$BGB = 1.280 * DBH^{1.17} \tag{2}$$

$$B = AGB + BGB \tag{3}$$

Where, AGB is aboveground biomass (kg), BGB is belowground biomass (kg), DBH represents the diameter at breast height (cm), and B is tree biomass (kg). Moreover, Khan et al. (2024) reported that carbon stock value could be estimated by multiplying biomass by 0.47 as follows.

$$AGC = AGB * 0.47 \tag{4}$$

$$BGC = BGB * 0.47 \tag{5}$$

$$C= AGC + BGC \tag{6}$$

Where, AGC is the above carbon stock (kg), BGB is the below carbon stock (kg), 0.47 is carbon conversion factor for AGB and BGB, and C represents tree carbon stock (kg). Furthermore, CO_2 sequestration potential was estimated by multiplying tree carbon stock by 3.67(Khasanah & van Noordwijk, 2019).

$$CS= C * 3.67 \tag{7}$$

Where, CS is carbon sequestration (kg) and 3.76 is the conversion factor of carbon stock to carbon sequestration. The mean annual carbon sequestration rate was estimated by dividing carbon sequestration by tree age (Du et al., 2024).

$$VCS = \frac{CS}{t} \tag{8}$$

Where, VCS is the mean annual carbon sequestration (kg/y converted to t/ha/y) and t is tree age (y).

The sample plot data was summarized into tables, visualized by graphs, and interpreted descriptively with existing literature. Moreover, One-way Analysis of Variance (ANOVA) test was applied using SPSS version 17.0 to determine the differences in carbon stock and litter production among the planting periods. ANOVA result that showed a significant difference was further subjected to LSD test (Verma, 2013). A simple linear regression analysis was also used to assess the relationship between litter production and mangrove density (Bingham & Fry, 2010).

3. Results and Discussion

Stand Density and Diameter

The analysis showed that the stand density of *Avicennia alba* planted in mangrove rehabilitation area varied according to age as presented in Table 1. The highest was at Station 3 with 94 individuals/100 m^2 while the lowest was at Station 1 with 59 individuals/100 m^2. This difference was due to stand age because older plants were expected to have lower density than younger plants. The trend was in line with the previous research that showed a decrease in mangrove stand density as plant age increased due to mortality factors caused by tree competition, self-thinning, and environmental conditions (Kamara & Kamruzzaman, 2020). Moreover, some environmental factors influencing mangrove mortality include high salinity, sedimentation, and dry periods, as well as low rainfall and humidity (Lovelock et al., 2009).

Figure1. Research area map.

Table 1. Stem density and dbh of *Avicennia alba* in different mangrove rehabilitation stations

Station	Plot number	Stem density (trees/100 m^2)	Average Stem density (trees/100 m^2)	Dbh (cm)	Average Dbh (cm)
1 (Planted in 2017, age 6 y)	1	59	59±3.68	3.89±0.83	4.03±0.98
	2	54		3.56±0.68	
	3	63		4.64±1.03	
2 (Planted in 2018, age=5 y)	1	98	91±8.06	3.00±0.93	3.48±1.08
	2	80		3.71±1.00	
	3	96		3.72±1.13	
3 (Planted in 2019, age = 4y)	1	94	94±1.63	2.34±0.78	2.81±0.88
	2	96		3.00±0.82	
	3	92		3.10±0.85	

Source: Primary data processing.

The highest diameter recorded for mangrove at Station 1 (planted in 2017 or 6y old) was 4.03 cm, while the lowest was at Station 3 (planted in 2019 or 4y old) at approximately 2.81 cm which corresponded with the age of *Avicennia alba* in Table 1. The trend showed that the increase in the diameter of trees tended to older age. This result was in line with the explanation of previous research that mangrove diameter increased in direct proportion to age and inversely to the increment in stand density (Salmo et al., 2013; Aye et al., 2023). Research also showed that the increase in diameter could be due to the sufficient light intensity received and the number of leaf related to photosynthesis (Suwa et al., 2008). Moreover, lower tree density provides lighting space and reduces tree competition which causes an increase in the dimensions and weight of mangrove stems (Khan et al., 2013). Older mangrove produces sufficient litter, increases soil fertility, and provides the nutrients needed by plants (Ye et al., 2013).

Biomass Potential

The highest biomass for tree level was at Station 1 with 7.61 kg/tree while the lowest was at Station 3 with 3. 44 kg/tree. The analysis showed that the potential biomass was closely related to tree diameter size and age as presented in Table 2. The trend was in line with the report of previous research that the factors contributing to biomass were stem density, diameter, mangrove type, wood density, and species diversity (Zaman et al., 2023). The differences in age and type of mangrove led to the production of varying amounts of biomass (Sahu & Kathiresan, 2019). Older mangrove had a larger diameter, wood density, and biomass than younger mangrove (Sarno et al., 2020; Camacho et al., 2011). Therefore, a tree with a larger diameter tended to have a larger biomass (Abeysekara et al., 2019). The process could also be influenced by some environmental factors such as nutrient availability in the soil and water levels (Constance et al., 2022).

Biomass potential of *Avicennia alba* in AGB part was more significant than BGB. It was also observed that the proportion relatively increased with age in the range from 61.32% to 63.02%, as presented in Figure 2. The result was supported by previous research that the proportion of biomass stored AGB was more significant than BGB (Njana et al., 2016; Suhaili et al., 2020). AGB biomass factor includes the high fraction of tree trunks and branches contributing more to biomass than the roots and is considered to have a strong relationship with tree diameter. The specific gravity of wood and crown diameter also determine biomass of mangrove root section in addition to tree diameter (Zanvo et al., 2023).

Carbon Storage

Carbon storage of *Avicennia alba* at tree level was found in Station 1 to be 3.58 kg C/trees, Station 2 had 2.66 kg C/ trees, and Station 3 had 1.62 kg C/trees. Meanwhile, the values at the stand level were 21.33 t C/ha, 24.07 t/ha, and 15.20 t C/ ha, respectively. One-way ANOVA test conducted also showed there was no significant difference in carbon storage at the stand level for different stations (p-value=0.65), as presented in Table 3. The trend at tree level showed that carbon storage increased with age and diameter. The results for the stand level showed that the high mortality rate at Station 1 caused a decrease in stem density, biomass, and carbon storage compared to Station 2. This was in line with the report of previous research that the factors influencing carbon storage were tree biomass, stem density, diameter, species, and age (Bai et al., 2021). Moreover, carbon storage value increased with biomass and both were related to soil physico-chemical parameters, tree diameter, and tree density. This was based on the observation that higher parameter values increased biomass and carbon stored (Cadiz et al., 2020).

The increase in age was directly proportional to the increment in diameter and biomass (Purnamasari et al., 2020). However, the significantly high mortality in mangrove ecosystems could reduce stand density, biomass, and carbon storage (Gomes et al., 2021). The high mortality recorded in the rehabilitation program was due to the failure in modifying hydrological connectivity without considering climatological parameters, specifically rainfall, air temperature, humidity, and evaporation, which led to hypersaline conditions (Jaramillo et al., 2018). Another cause was climate change which increased the occurrence of droughts and storms, subsequently leading

Table 2. Stem density, AGB biomass, BGB biomass, and total biomass of *Avicennia alba* planted in different mangrove rehabilitation stations

Station	Plot	Stem density (trees/100 m^2)	AGB (kg/trees)	BGB (kg/trees)	Total Biomass (kg/trees)
1 (Planted in 2017, Age= 6y)	1	59	4.29	2.55	6,84
	2	54	3.41	2.08	5,49
	3	63	6.69	3.81	10,50
	Average	59±3.68	4.80±1.38	2.81±0.73	7,61±2.11
2 (Planted in 2018, Age=5y)	1	98	2.47	1.53	4.00
	2	80	3.99	2.38	6.37
	3	96	4.15	2.46	6.61
	Average	91±8.06	3.54±0.76	2.12±0.42	5.66±1.17
3 (Planted in 2019, age 4y)	1	94	1.37	0.90	2.27
	2	96	2.38	1.49	3.87
	3	92	2.58	1.60	4.19
	Average	94±1.63	2.11±0.53	1.33±0.14	3.44±0.84

Source: Primary data processing.

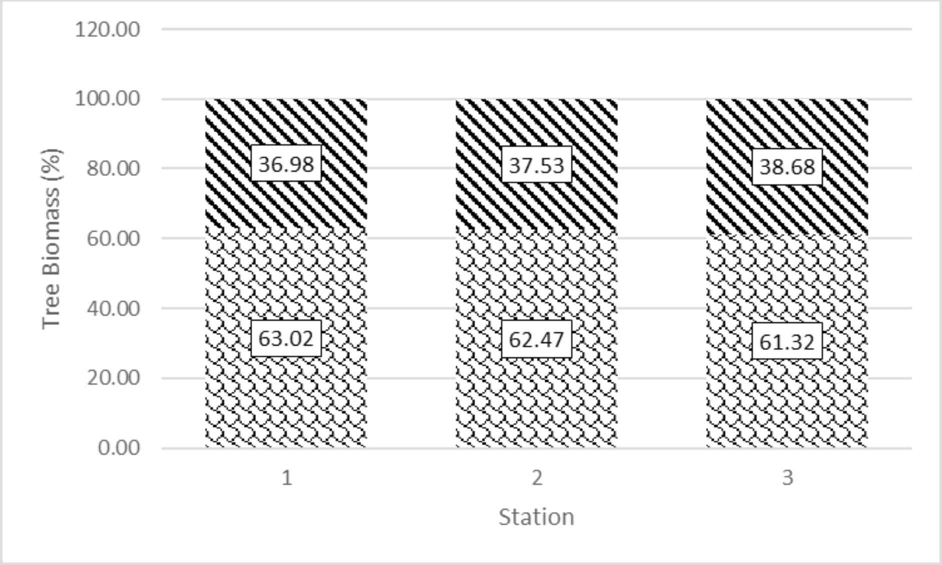

Figure 2. The proportion of AGB and BGB to total biomass in different stations.

to degraded mangrove (Sippo et al., 2018). In addition to tree density, biomass content of a forest was also found to be nearly dependent on photosynthesis (Alongi, 2009). Previous research also showed that each species contributed differently to the total biomass and carbon storage at the stations (Zulhalifah et al., 2021).

CO_2 Sequestration

The mean annual CO_2 sequestration rate in Station 1 was 13.00 t/ha/y, Station 2 had 17.65 t/ha/y, and Station 3 recorded 13.94 t/ha/y. The factors influencing CO_2 sequestration from the atmosphere are similar to those recorded for carbon storage and include stem density, diameter, species, and age of mangrove as presented in Table 4. Mangrove forests have great potential to absorb CO_2 from the atmosphere (Alongi, 2014) and convert it into organic compounds through photosynthesis which are used for vertical and horizontal growth (Malerba et al., 2023).

Tree biomass increased at a certain age in a sigmoid manner with the highest recorded at the intersection of mean and current annual growth. After this intersection, the growth is relatively stagnant according to stand dynamics which include growth, recruitment, and mortality (Bao et al., 2022). The increase in diameter of trees also tends to be caused by increment in biomass storage associated with the conversion of more carbons (Iksan et al., 2019). Moreover, there is often higher CO_2 uptake when the total carbon and biomass content of plants are equal (Martuti et al., 2017). The factors influencing the ability of plants to absorb CO_2 include temperature, sunlight, water availability, and total leaf area (Trissanti et al., 2022). It has also been reported that salinity, pH, and Substrate texture affect the healthiness and productivity of mangrove (Dimyati et al., 2022). Previous research further showed that the age and growth phase of *Avicennia marina* had higher CO_2 absorption than *Rhizophora stylosa* and *Bruguiera gymnorrhiza* (Kathiresan et al., 2013).

The Correlation of Diameter with Biomass, Carbon Storage, and CO_2 Sequestration

The equation B = -6.6706 + 3.558*Dbh shows the relation between tree diameter and biomass, C= -3.1352+ 1.6722*Dbh for tree diameter and average carbon storage, while S=-11.496+

Table 3. Stem density and carbon storage in different mangrove rehabilitation stations

Station	Plot	Stem density (trees/100 m^2)	Carbon storage (kg C/trees)	Carbon storage (t C/ha)
1 (Planted in 2017, age=6y)	1	59	3.22	18.98
	2	54	2.58	13.93
	3	63	4.93	31.08
	Average	59±3.68	3.58±0.99	21.33±7.19
2 (Planted in 2018, age=5y)	1	98	1.88	18.45
	2	80	2.99	23.95
	3	96	3.11	29.81
	Average	91±8,06	2.66±0.55	24.07±4.64
3 (Planted in 2019, age=4y)	1	94	1.07	10.02
	2	96	1.82	17.48
	3	92	1.97	18.11
	Average	94±1,63	1.62±0.40	15.20±3.67

Sources: Primary data processing.

Table 4. Stem density, CO_2 sequestration of *Avicennia alba* in different mangrove rehabilitation stations

Stations	Age (y)	Plot	Stem Density (trees/100 m^2)	CO_2 Sequestration (kg/trees)	CO_2 Sequestration (t/ha)	Mean annual CO_2 Sequestration rate (t/ha/y)
1 (Planted in 2017)	6	1	59	11.79	69.58	11.60
		2	54	9.46	50.48	8.41
		3	63	18.09	113.95	18.99
		Average	59	13.11±3.64	78.00±26.59	13.00±4.45
2 (Planted in 2018)	5	1	98	6.9	67.64	13.53
		2	80	10.98	87.82	17.56
		3	96	11.39	109.31	21.86
		Average	91	9.76±2.02	88.26±17,01	17.65±3.40
3 (Planted in 2019)	4	1	94	3.91	36.73	9.18
		2	96	6.68	64.10	16.03
		3	92	7.22	66.39	16.60
		Average	94	5.93±1.45	55.74±13.47	13.94±3.37

Sources: Primary data processing

6.1316*Dbh is for tree diameter and CO_2 sequestration. All slope coefficients showed that DBh was positively related to biomass, carbon storage, and CO_2 sequestration with the r-square (r^2) estimated to be 0.9734 as presented in Figure 3. Moreover, the result further showed that the average diameter of trees increased with age. The average CO_2 sequestration in the rehabilitated mangrove forest area was found to be 74 t/ha. This was higher than the value recorded by Sondak (2015) in North Sulawesi which was approximated at 39.37 t/ha for the 11,691 ha. The variation could be due to differences in the area as well as the types and conditions of mangrove. Global comparison further showed that the blue carbon ecosystem was capable of absorbing 42 billion tonnes of CO_2, the trend in Korea was 1.01 million tonnes, Abu Dhabi had 39.16 million tonnes, and Indonesia had 138.23 million tonnes (Sondak, 2015).

The results showed that biomass and carbon storage of *Avicennia alba* increased at an older age and larger tree diameter. The trend showed the close relation of tree diameter to biomass, carbon storage, and absorption. The result was in line with the submission of previous research that stem diameter increased with biomass value and carbon stock (Prasetyo et al., 2017; Malik et al., 2022). Older mangrove was observed to have greater dbh, biomass, and carbon stock (Acosta et al., 2024). Moreover, stand height could also influence biomass value because the increase in diameter tended to cause an increment in biomass value and carbon storage (Luu et al., 2020).

Tree biomass content is the representation of the total organic material produced through photosynthesis which is the process of absorbing and converting CO_2 from plants into carbohydrates for subsequent distribution in the plant body and storage in organs such as leaf, stem, twig, flower,

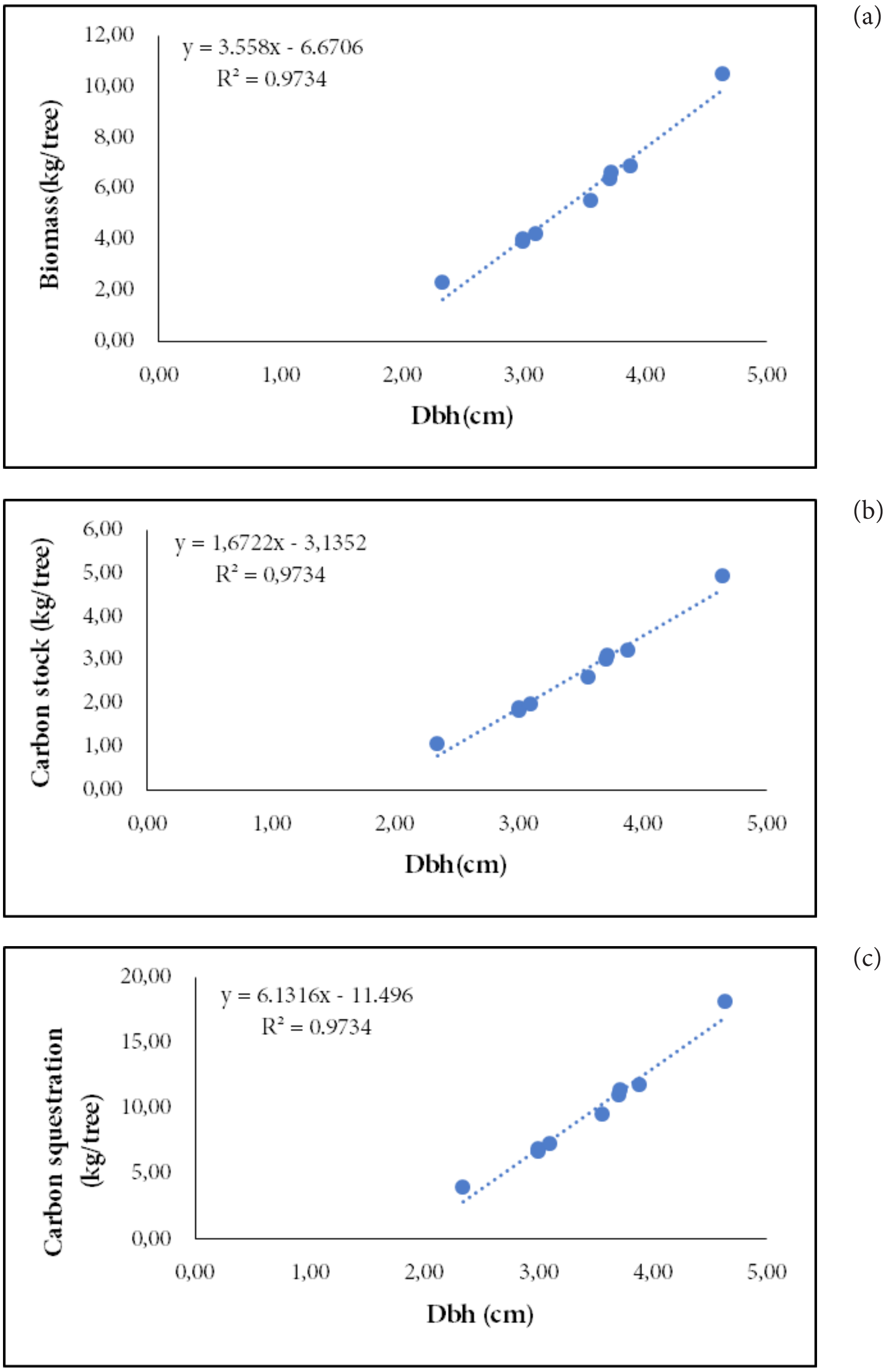

Figure 3. Relationships of diameter with biomass (a), carbon storage (b), and CO_2 sequestration (c)

and fruit (Rivera-Monroy et al., 2017). The main element of biomass is carbon and this shows trees with high biomass have a high carbon stock value (Trissanti et al., 2022). Therefore, the changes in tree size distribution, including diameter and height, affect biomass and carbon dynamics. The trend is because a larger tree diameter increases biomass and carbon stock. The biotic factors that significantly influence diameter growth include species diversity, stand structure, abiotic factors, and salinity. Previous research showed that high salinity caused tree diameter growth to be lower (Ahmed et al., 2023). It was also reported that climatic factors such as higher rainfall led to an increase in mangrove tree diameter while temperature had a negative correlation (Djamaluddin, 2019). An abundance of pneumatophores often leads to an increase in tree diameter and is considered proportional to the mud content and sediment oxygen levels (Al-Khayat & Alatalo, 2021).

The depth of seawater is another factor influencing an increase in the diameter of mangrove. This was observed from the report that deeper inundation depths inhibited the increase in the diameter more than shallower depths (Nguyên Lý et al., 2016). Soil chemical fertility also has an important role in the growth of mangrove. The trend was observed from the ability of sufficient nutrients, such as phosphorus, magnesium, calcium, and sulfur, to increase the growth. This is identified from the importance of phosphorus in plant metabolism as well as magnesium in chlorophyll function and relative abundance in seawater compared to other nutrients. Meanwhile, elements such as CA^{2+} and K^{+} were reported to be most antagonistic to Mg^{2+} (Constance et al., 2022). The analysis of physical soil fertility also showed that mangrove grew optimally in soils with light, medium, and heavy textures, a pH of 6-8.5, and high organic content (Munandar et al., 2011). Furthermore, the nitrogen content and diversity of mangrove species positively correlated with the growth and biomass. This is because high species diversity increases stability and productivity through processes of association, complementarity, substitution, and selection. Another important observation is that species with dominant productivity have larger tree sizes and biomass (Bai et al., 2021).

Litter Production

Litter produced by *Avicennia alba* at Station 1 was 4.32 t/ha/y, Station 2 was 3.65 t/ha/y, and Station 3 was 3.23 t/ha/y. The result also showed that older mangrove had larger diameters and more litter. One-way ANOVA analysis showed that the condition was insignificant at the 95% confidence level (p-value=0.131) as presented in Table 5 and Figure 5. Meanwhile, the trend was in line with the observation of previous research that litter production rates were influenced by the type and age of mangrove (Rahardjanto et al., 2022). Several plant growth cycles, such as wilting, senescence, death, age, diameter, the density of trees, and environmental factors in the form of rainfall, wind, and temperature generally influence litter production. This is observed from the fact that rainfall and water temperature are inversely proportional to production while relative humidity has a direct relationship. Previous research also showed that mangrove with larger tree diameters produced more litter (Dali, 2023). Further observation showed that litter production was directly related to mangrove density but inversely to salinity (Dewiyanti et al., 2021).

Table 5. Dbh and litter production of *Avicennia alba* in different mangrove rehabilitation stations

Stations	Dbh (cm)	Litter production (t/ha/y)
1 (Planted in 2017)	4.03±0,98	4.32± 1,82
2 (Planted in 2018	3.48±1,08	3.65± 0,79
3 (Planted in 2019)	2.81±0,88	3.23± 1,37

Sources: Primary data processing.

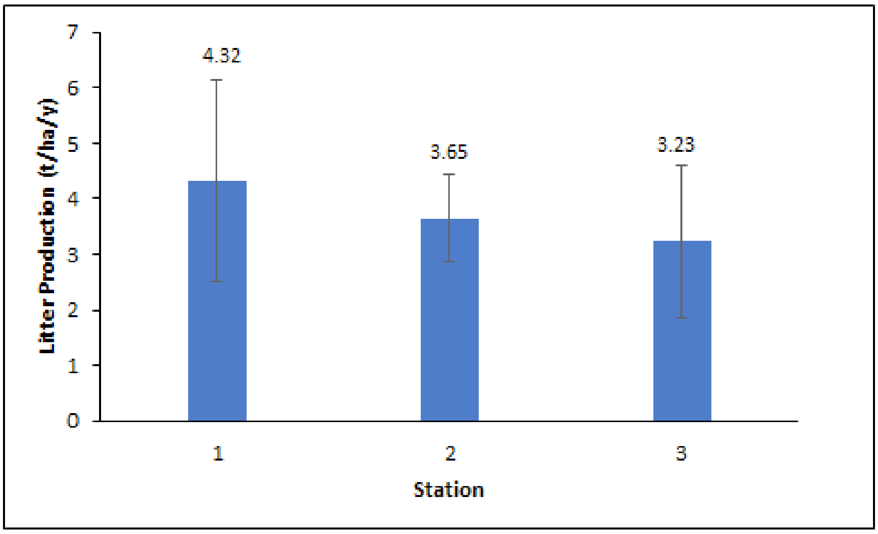

Figure 5. Litter production of *Avicennia alba* in different mangrove rehabilitation stations

Table 6. The contribution of different *Avicennia alba* parts to total litter production in several mangrove rehabilitation stations.

Stations	Trees Part	Litter production proportion (%)
1 (Planted in 2017)	Leaf	85.50±4.06
	Twig	12.30±5.26
	Flower/Fruit	2.20±1.25
2 (Planted in 2018)	Leaf	80.64±2.04
	Twig	10.85±3.68
	Flower/Fruit	5.50±2.60
3 (Planted in 2019)	Leaf	76.50±19.92
	Twig	22.37±19.78
	Flower/Fruit	1.14±0.47

Sources: Primary data processing.

The analysis showed that leaf contributed more to litter production than twig and flower or fruit in the three stations. It was observed the proportion of litter produced by leaf increases with age and diameter as presented in Table 6. The result was in line with the report of previous research that leaf contributed the largest to the total litter produced by mangrove forests (Imgraben & Dittmann, 2008). The trend is because leaf biologically forms faster than reproductive organ, twig, and flower or fruit (Arfan et al., 2018). Leaf also tends to be shed more easily by gusts of wind and rain (Mulya & Arlen, 2018). The high contribution of leaf was also related to the adaptation of plants to the reduction of water loss and the ability to survive at high salt levels (Yunus et al., 2023).

The result showed that the average litter production was estimated at 4.2 t/ha/y and this was lower than the 9.9 t/ha/y recorded in the waters of Teluk Sepi Beach (Zamroni & Rohyani, 2008) and 12.9 t/ ha/y in Tiris Indramayu mangrove forest (Sukardjo, 2014). Litter is considered important in mangrove ecosystems to store carbon, provide plant nutrition (Pradisty et al., 2022), and contribute 26% to fish food (Awuku et al., 2022). Moreover, natural mangrove ecosystems that are still intact tend to have higher species diversity than those rehabilitated. This further leads to the production of more litter and an abundance of bacteria which are capable of increasing the decomposition rate to subsequently enhance the fertility of the soil and productivity of the ecosystem in absorbing and storing carbon (Azman et al., 2021). The application of good rehabilitation methods, including the consideration of the natural condition before damage, the suitability of the species for the place of growth, socio-economic conditions, and community participation, is important to improve mangrove silviculture (Gerona-Daga & Salmo, 2022).

The Role and Challenges of Mangrove Ecosystems for Carbon Offset

The analysis showed that carbon sequestration at mangrove rehabilitation stations was found only in *Avicennia alba* which was naturally in the foremost zone. The potential level of 13.00 – 17.65 t/ha/y recorded was observed to be lower than the values in the natural mangrove ecosystems with complete 3 zone structures estimated at 78.9 t/ha/y by Sugiana et al. (2023). Local government data also showed the importance of the Riau Province mangrove forest in reducing CO_2 emissions. The area of the forest up to 2020 was 158,053 ha and the total CO_2 emissions in the whole of the province from 2010 to 2019 was 207.02 Mt/y. The trend further showed that the average for the provincial area of 89,935.90 km^2 was 23.02 t/ha/y and the sources were the forestry sector at 62.9%, energy at 33.2%, agriculture at 1.3%, and waste at 2.6 % (Riau Province Government, 2022). Moreover, the average annual carbon sequestration rate assumed for the natural ecosystem was 78.9 t/ha/y and the ability of mangrove forest to offset CO_2 emissions was 12.47 Mt/y or 6.0 % of the total at the provincial level (Sugiana et al., 2024). The data showed that the forest experienced damage from 2009 to 2019 at a deforestation rate of 3.1 %/y or approximately 477.01 ha/y due to several factors, including aquaculture development, oil palm plantation expansion, agriculture, coastal area development, logging, mining, abrasion, and natural disasters (Oktorini et al., 2022).

Community-based mangrove rehabilitation programs are a potential method to increase the degraded cover (Quevedo et al., 2023). Agroforestry methods, specifically silvofishery, are a win-win solution to achieve rehabilitation goals by optimizing mangrove function and integrating the plantation process into fisheries cultivation (Kusumaningtyas et al., 2020). Moreover, the combination of rehabilitation programs and ecotourism can increase local community income, environmental education, and community awareness (Nuraeni & Kusuma, 2023). The trend shows the possibility of combining and registering rehabilitation, silvofishery, and ecotourism programs as carbon offset programs using relevant standards. The application of carbon offset project could allow the community to receive more optimal resources and technology from multi-party support to ensure more sustainable community-based mangrove management by balancing the economic, ecological, and social functions (Karpowicz et al., 2024).

4. Conclusion

In conclusion, the potential for biomass and carbon storage at tree level was directly proportional to the diameter and age of mangrove. This was based on the fact that older mangrove forest had higher stem diameter and biomass compared to younger mangrove forest. At the stand biomass level, carbon stock and sequestration were influenced by stand density. This was because mangrove with greater dbh and tree density had greater biomass, carbon stock, and sequestration. Furthermore, the magnitude of death in older mangrove forest showed that biomass, carbon stock, and sequestration at the stand level in the three stations were not significantly different at the 95% confidence level. Diameter was also directly related to biomass and carbon sequestration. The results showed that litter produced by *Avicennia alba* was directly proportional to the stand diameter and age but was insignificant at the 95% confidence level. Leaf was found to be the most significant contributor to litter produced and the proportion increased with age and stand diameter. Compared to other mangrove ecosystems, the research area had a lower level of litter production. The results were expected to serve as input to plan for the rehabilitation and maintenance of mangrove in order to increase the productivity for ecosystem services, specifically in reducing CO_2 emissions, protecting beaches, and supporting sustainable development in coastal areas.

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